

The 8th US Climate Modeling Summit Report

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The 8th USCMS Co-Chairs

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Summary

The 8th US Climate Modeling Summit (USCMS) was held in a hybrid format at the College Park Marriott Hotel and Conference Center in Hyattsville, MD. The Summit consisted of a 1.5-day Topical Workshop on Water Cycle and Water Security during 2-3 August 2022 and a Summit Meeting on 3-4 August 2022. The Workshop engaged scientists, primarily from the modeling centers and national laboratories, working on water cycle and water security related areas. The USCMS, involving core members (see Appendix C) and the US Global Change Research Program's (USGCRP) Interagency Group on Integrative Modeling (IGIM) managers, continued to be an opportunity for high level modeling discussions to enhance coordination and collaborations across the centers. As in past years, the Summit Meeting was dedicated to the progress made at the modeling centers with other updates since last year's meeting and discussions on various ongoing efforts and emerging opportunities and challenges. A concern raised by the modeling center participants was the rather sparse participation of the program managers both at the Topical Workshop and the Summit Meeting. The meeting concluded with planning coordinated activities among the modeling centers for the upcoming year, including the 9th USCMS. A short-term action item is drafting of a Model Intercomparison Project protocol to understand the trends in the satellite observations of the Earth's energy imbalance.

Background on USCMSs and Workshops

To improve the coordination and communication of national climate modeling goals and objectives, the USGCRP's IGIM has been convening an annual USCMS since 2015. The Summit brings together representatives from the US climate model development centers and operational climate and weather prediction programs. Specifically, two representatives – one lead and one additional delegate – from each of the following groups are invited to participate in the Summit: NOAA National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) and Environmental Modeling Center (EMC); NOAA Geophysical Fluid Dynamics Laboratory (GFDL); NASA Goddard Institute for Space Studies (GISS); NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS); NSF National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM); and DOE Energy Exascale Earth System Model (E3SM) (Appendix C).

As envisioned by the IGIM, the high-level USCMS objectives include:

1. Developing a shared understanding of modeling groups' directions and implementation strategies;
2. Identifying opportunities for enhanced coordination and synergy among modeling groups; and

3. Identifying outreach opportunities to user communities.

Starting in 2017, a topical workshop has also been organized under the auspices of the USCMS and in conjunction with the annual meeting. These workshops serve as a venue for focused scientific and technical information exchange on a high-priority modeling-related topic identified by the modeling centers together with the IGIM, and they may include invitees from the broader community.

Workshop Agenda

The 8th USCMS agenda and the link to presentations are given below in Appendix B. The agenda consisted of three parts. The first part was devoted to brief updates from activities that started at previous USCMS meetings and a summary of this year's Workshop (see below). In the second part, the centers provided updates on their science, priorities, challenges, and plans, focusing on USGCRP-relevant efforts. These presentations generally covered the centers' new model configurations, developments, frameworks, initiatives, and some results of interest to the other centers. Because the updates are too detailed to be summarized in this report, the reader is referred to the presentations available via the link provided in Appendix B. The last part of the Summit was dedicated to discussions on several ongoing efforts and emerging / future opportunities and challenges, focusing on possibilities for coordinated activities as summarized below.

Summary of Activities Since the Previous USCMS

Progress was reported from three projects that were initiated at previous USCMS meetings.

The *world-avoided* mini Model Intercomparison Project (mini-MIP) aimed to look at the impacts of the Clean Air Acts on air quality and climate. This project, led by Jean-François Lamarque (NCAR), developed appropriate emission scenarios. A set of simulations were performed by NCAR (CESM2), DOE (E3SM), NASA GISS (modelE), and NOAA GFDL (ESM4). Preliminary results showed significant impacts of US emission trajectories on global surface ozone concentrations and particulate pollutions. Unfortunately, further progress involving more detailed analysis of the simulations focusing on impacts on climate, air pollution, and health has not been realized due to lack of resources. With Lamarque's departure from NCAR, it is unlikely that this project will be completed.

Following the 2020 USCMS Workshop on Aerosol – Cloud Interactions, Johannes Mülmenstädt (PNNL) initiated a collaborative project, involving participation of all six modeling centers. The project combined observational data with model results and theoretical studies to better understand the physical realism of aerosol-induced cloud drying across models. The research plan included the following steps: 1) Evaluation of the relationships between cloud droplet number concentrations and liquid water path; 2) investigation of physical realism of the entrainment fluxes in models; 3) testing process interpretation of satellite correlations; and 4) linking entrainment mediated aerosol – cloud interactions with cloud feedbacks. Mülmenstädt successfully completed the project with two manuscripts in preparation.

The 2021 USCMS Topical Workshop was on Predictability Limits Arising from Model and Prediction System Challenges. As an outcome of the Workshop, Gokhan Danabasoglu (NCAR)

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recently submitted a proposal entitled “Is better representation of modes of variability related to reduced model biases and better simulations of extreme events in US climate models?”, with four modeling centers participating in the effort. The representations of modes of variability (MoV) have been steadily improving in recent versions of Earth system models. These improvements result from better representation of related processes either through increased model resolution, improved physics, or through more gradual and cumulative model advances occurring over many years. Better representations of MoVs clearly improve model fidelity, but it is not clear if and how improvements in MoVs drive reduced biases, for example, of precipitation, surface temperature, and associated extreme events. It is the intent of the proposal to fill in this research and knowledge gap. The overarching hypothesis of the project is “Better representation of MoVs is associated with reduced model bias; better representation of teleconnections and regional climate variability over land; and improvements in capturing extreme event statistics.” A goal is to generate a large, multi-dimensional matrix of performance scores for MoVs, model biases, associated teleconnections, and representation of extremes for a set of US models. An aim is to provide a summary assessment of the relationships between MoVs and these other aspects of model performance with a focus on extremes. The project will then investigate related process level relationships, comparing models with different levels of fidelity to identify differences that might explain the inter-model spread. In addition to routine analysis methods, machine learning and explainable artificial intelligence tools will be an important element of the project to probe such relationships.

2022 Topical Workshop

The water cycle sustains life and supports a wide range of human activities. While global mean precipitation is projected to increase at ~2% per 1°C of warming, precipitation over land is expected to be distributed more unevenly both in space and time with global warming, driving larger disparity in water availability around the world. Exacerbated by increasing weather extremes as well as increasing water demand to support the growing populations, society’s ability to provide reliable water for health, livelihoods, and production while maintaining water related risks at the cyclostationary level (to which managers and governments were accustomed in the absence of global warming) is increasingly being threatened. With the changing water cycle and water security (WCWS), there are increasing demands for weather and climate forecasts and projections to improve water management and planning. However, weather and climate models exhibit noticeable biases in simulating different aspects of the water cycle, undermining their credibility for providing actionable information to address the WCWS challenges facing the world.

Recognizing the needs to advance predictions and projections of water cycle changes that threaten water security, “Water Cycle and Water Security” was selected as the topic for the 2022 USCMS Topical Workshop. Organized into three sessions focusing on: (i) model development and evaluation; (ii) insights from observations and modeling; and (iii) emerging approaches including ultra-high-resolution modeling and Artificial Intelligence / Machine Learning

(AI/ML), workshop participants were charged to identify the gaps in understanding and modeling WCWS and explore opportunities for addressing these gaps through collaborations among the US climate modeling centers and the broader communities.

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The workshop was held in a hybrid format during 2-3 August 2022 just before the Summit Meeting. Each session featured several 15-minute presentations and parallel breakout sessions to discuss gaps and opportunities. The workshop agenda is included in Appendix A. Briefly summarized below are the presentations given in each session and key takeaways from the presentations and breakout group discussions.

i. Model development and evaluation

This session featured 6 presentations on model development and evaluation efforts at the US climate modeling centers, including a university-led Climate Process Team project involving several modeling centers, to improve modeling of different aspects of WCWS. The presentations highlighted development efforts to improve model representations of subgrid scale processes such as hillslope hydrology and the impacts of subgrid land surface heterogeneity on land atmosphere interactions through changes in surface fluxes and by inducing secondary circulation that affects clouds and precipitation. Major efforts have also been devoted to representing human-Earth interactions through coupling of integrated assessment models with Earth system models, modeling irrigation and reservoir operations that regulate streamflow, and modeling urban hydrology and floods. As large populations reside in coastal regions, efforts have also been devoted to improving modeling of land-river-ocean processes in the coastal zones, highlighting development of unified surface meshes to facilitate two-way coupling of land, river, and ocean processes important for modeling compound flooding events.

While increased model complexity and resolution have led to some improvements in modeling water cycle processes such as precipitation, large uncertainty remains in understanding past and projecting future water cycle changes. More systematic calibration of model parameters through parameter perturbation experiments may further enhance accuracy of simulations. More efforts are also needed to evaluate model simulations using a variety of water cycle metrics, diagnose the sources of model biases and uncertainties, and improve understanding of model sensitivity to parameterizations and resolutions.

ii. Insights from observations and modeling

This session included 12 presentations by the modeling centers and the university community on their efforts to improve understanding of water cycle changes and address water security challenges. Several presentations focused on extreme events including floods, droughts, atmospheric rivers, extreme precipitation, and compound extreme events. These presentations highlighted floods and droughts as complex interdisciplinary phenomena that are sensitive to a variety of biological and physical processes and human systems. Hence, drought responses in model projections cannot be generalized globally or across variables. Similarly, the impacts of climate change and water management on future flood risks may not be generalized across river basins globally. Anthropogenic emissions have intensified compound events. Ignoring the

compounding effects of inter-related hazards such as droughts and wildfires leads to underestimation of the risk.

Atmospheric Rivers (ARs) are major causes of heavy precipitation and flooding in the western US. The GFDL SPEAR model can skillfully forecast AR activity at a lead time of 9 months over California and Alaska, but in British Columbia and Washington/Oregon, AR forecasts may be hindered by predictability limits. Models generally projected increased frequency and intensity

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of ARs with warming. Models with water tracers are useful tools to understand AR changes. In contrast to the western US, extreme precipitation in the northeastern US is often associated with hurricanes. At high resolution, the SPEAR model can realistically simulate the frequency and variability of extreme rainfall in the Northeast. Very extreme rainfall ($> 150 \text{ mm day}^{-1}$) is projected to be five times more likely by 2100.

Three presentations focused on large-scale water cycle changes in climate models. Water vapor trends have important implications for wildfires, but climate models are not able to capture the relatively negative vapor pressure trend compared to the expectation of increasing water vapor due to warming, particularly in arid and semi-arid regions, motivating the need for further investigations. Climate models robustly project reductions in surface relative humidity (RH) over land and increases over ocean, with both ocean and land playing important roles in the contrasting land-ocean changes. Reduced RH over land has important implications for convection, but modeling experiments suggest rather complex responses that deserve more investigations. Climate models exhibit large uncertainty and biases in the runoff sensitivity (i.e., change in runoff per 1°C of warming or per 1% of precipitation change). Constraining the model runoff sensitivity by the observed values can reduce model uncertainty by 50% and shift the multi-model mean projection for the future.

Lastly, three presentations focused on human influence on the water cycle. Irrigation introduces surface heterogeneity that influences land-atmosphere coupling, but detailed observations and improved modeling are needed to better understand the implications for local climate. Besides local effects, irrigation may also have remote influences. Modeling experiments suggest that irrigation in the Middle East and South Asia has enhanced Sahel precipitation by reducing the gradient of moist static energy from the Sahara Desert to the Sahel, resulting in increased precipitation over the Sahel. Besides irrigation, climate models now represent many aspects of human influences on the food-energy-water nexus, such as groundwater extraction, reservoir operations, in-stream turbine for energy generation, and agricultural nutrient management. These modeling capabilities have allowed more diverse investigations of water security issues.

iii. Emerging approaches: ultra-high-resolution modeling and AI/ML

This session included 9 presentations highlighting development and use of ultra-high-resolution models and AI/ML approaches to model the water cycle. NCAR noted several collaborative efforts with university groups on enabling cloud-permitting coupled modeling, high-resolution modeling using regional-refined meshes, and harnessing data and AI/ML to improve parameterizations, calibrate models, and improve climate projections. GFDL described its global storm-resolving model (X-SHIELD) and model simulations to investigate climate response to $4\times\text{CO}_2$ and sea surface temperature warming. They also discussed their efforts to use ML –

trained using X-SHiELD simulations – for online bias correction of the lower resolution model (SHiELD). At NOAA NCEP, the UFS global coupled models are being advanced for modeling at convective-allowing scales. AI/ML approaches are broadly used in air quality applications and to improve model physics. AI/ML are also used in data assimilation, postprocessing, and product generation. The E3SM global cloud-resolving modeling effort was briefly introduced, highlighting the use of C++ and Kokkos for performance portability. Global cloud-resolving simulations performed at ~3.25 km resolution and regional-refined simulations of a mid-latitude severe convective storm at ~3.25 km over the eastern US show realistic simulations even without significant tuning.

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At NASA GSFC, ML was used to understand non-stationarities in water cycle. With land data assimilation, Noah-MP showed intensification of the water cycle in recent decades. Trained using this framework, an ML emulator was developed to learn the human impacts on water cycle. Driven by CMIP6 historical and future projections, the ML emulator can be used to project human impacts on water cycle. At NASA GISS, ML is being used to accelerate model development, with an ongoing focus on developing ML emulators trained on perturbed physics ensembles (PPE) for global tuning of model parameters. ML tuning has been shown to improve model simulations of the PDF of rain-rates, aerosol indirect radiative forcing, atmospheric rivers, ocean carbon cycle, and other aspects.

The CliMA efforts were introduced, highlighting ML as applications to the inverse problem rather than supervised learning. In brief, subgrid-scale flow inside a climate model grid box is decomposed into coherent and incoherent parts, with the coherent part modeled using coarse grained equations and the incoherent part modeled by closure functions, which can be modeled using parametric models or ML such as neural networks. This approach produces the first unified model of turbulence and clouds that captures all of Earth's cloud regimes. At NCAR, km-scale regional simulations have been used to investigate hydrological cycle changes with global warming. These simulations are approaching observational quality but simulating water cycle in the Anthropocene requires incorporating human impacts such as dam regulations. In the last presentation, two examples were used to illustrate the use of big data analytics in securing the future of water, energy, and food. In the first example, agricultural practice in India is unsustainable and leads to acute water stress. Big data are used to learn about the current water stress, and data driven predictive techniques and process optimization are used to remove the water stress to achieve food security. In the second example, extreme temperatures under climate change will reduce yields for several major crops in the US. Using Bayesian learning, crop yields can be predicted based on technology trends, temperature, and water stressors. Employing systems optimization, crop switching strategies can be predicted to mitigate yield losses.

iv. Key takeaways

In the breakout sessions, workshop participants noted the following needs and opportunities. On model development and evaluation:

- There is a need to improve modeling of streamflow, fire weather, vegetation, and land use in land models to better address water security issues. Model accuracy can be improved by evaluating parametric and process-level uncertainty in models.

- Developing a hierarchy of land surface models is useful for different applications. Such model hierarchy may be accompanied by a hierarchical model evaluation approach and benchmarks, improving our understanding of model biases to inform development efforts.
- The benefits of high spatial resolution modeling with respect to advancing process understanding of WCWS should be evaluated and documented more systematically. Similarly, the challenges associated with high-resolution ensembles (protocol, data storage, targeted output, and resources) should be evaluated and documented. A workshop involving the climate modeling and computing communities could be a useful venue for such endeavors.

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- While instrument simulators have been used for over a decade in atmospheric modeling to facilitate apples-to-apples comparison between model simulations and satellite data, instrument simulators have not been used to evaluate land surface models. There is an opportunity to make use of satellite retrieval algorithms to develop instrument simulators for land surface modeling to improve efforts on model evaluation.
- To diagnose model biases, water tracers and isotopes can be added to models for comparison with isotopic measurements and to diagnose the propagation of model biases in connected variables. Quantifying the relationships among water cycle variables such as soil moisture, precipitation, and runoff using observations is useful for validating physical processes in models and build confidence in model representations of extreme events such as droughts.
- With increasing model resolutions, there is a need for high-resolution datasets to be developed to properly evaluate emerging fine-scale land models. In addition, developing and improving observation-based datasets of land variables can complement reanalysis data, which exhibit uncertainty in representing land-atmosphere coupling.
- There is a need to develop protocols for model intercomparison projects that focus on the two-way coupled land-atmosphere processes through offline land simulations combined with coupled land-atmosphere simulations with the atmosphere constrained by reanalysis.

On advancing insights on WCWS changes, workshop participants noted the following needs and opportunities:

- With irrigation represented in many climate models, the role of irrigation in the hydrological cycle through its local and remote impacts can be evaluated and compared among models.
- Centers can focus on identified WCWS-related topics from their own perspectives of time scales and interests. Centers could systematically examine some common biases and document their evaluations. For example, precipitation indices could be compared across models at different resolutions, time scales, etc.
- Several presentations identified uncertainties in modeling hydrological cycle such as uncertainties in the sensitivities to runoff and trends in surface vapor pressure. Centers

can jointly develop a set of hypotheses for the sources of model uncertainties/biases, perform numerical experiments to test the hypotheses, and develop emergent constraints to reduce uncertainties in future projections.

- Centers can collaborate on a focused mini-MIP on an identified WCWS topic following a common protocol. Such topics may include the impacts of water management and irrigation, experiments to test hypotheses of water vapor trends and surface relative humidity changes. Modeling experiments including water tracers/isotopes may improve understanding of water cycle dynamics and response to climate change.
- Collaborative efforts to develop new forcing data and evaluation datasets would benefit the modeling centers and the larger community.

On ultra-high-resolution modeling and AI/ML approaches:

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- High-resolution models should be part of the solution, not the entire solution as has been advocated in recent work¹. There is a need to improve understanding of where resolution matters. However, we cannot run long experiments or large ensembles at high resolutions, so a model hierarchy is needed. Idealized climate warming simulations can be done at high resolutions to explore cloud feedbacks, climate sensitivity, etc. Storyline simulations of specific events under present day and future climates are a good use of high-resolution models.
- Efforts should be invested to check where higher resolution models do not produce the same results as lower resolution models to determine where we need to focus efforts to represent these aspects better through improved parameterizations, emulators, or downscaling.
- There is a need for new satellite measurements of variables such as clouds to better evaluate global high-resolution models. There is also a need for better groundwater measurements, water use data, and post-processed datasets, as well as datasets with a closed water budget.
- Collaborative efforts on intercomparison of global storm resolving models, testing of doubly periodic storm resolving simulations in different climate regimes, and intercomparison of storyline simulations are useful for improving understanding and use of ultra-high-resolution models.
- There is a challenge to bring together the separate communities of global climate modeling vs. new ultra-high-resolution global modeling vs. regional modeling. Identifying opportunities for collaborations may advance understanding and uses of these approaches.
- There is a need for a multi-model-based synthesis of scenarios of past and future water appropriation for attribution and future projections of water cycle changes that account for human impacts.

Discussion Topics

The last part of the Summit, taking about half of the meeting time, was devoted to discussions on the topics summarized below.

Future Outlooks on CMIP and IPCC: This topic was a follow-up from last year's Summit. The discussion on the future of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) focused on the continued and growing relevance of CMIP in service to both the Intergovernmental Panel on Climate Change (IPCC) assessment process and as a critical source of information for both the climate science and impacts communities while acknowledging that the proliferation of numerous Model Intercomparison Project (MIP) simulations with the provision of data in support of IPCC led to considerable challenges at the modeling centers. Jean-François Lamarque described the creation of the new CMIP Project Office to institutionalize support, the vision for separation of the provision of core experiments in support of IPCC from specific science-centered MIPs, and the aspiration to optimize efforts

¹ Slingo, J., and Coauthors, 2022: Ambitious partnership needed for reliable climate prediction. *Nature Climate Change*, **12**, 499-503.

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for minimum human, computer, and CO₂ emissions while maximizing science and policy support outcomes. The requirements on resources are of a particular concern as the number of simulations being requested has increased considerably over CMIP generations, with many new MIPs added on a continuous basis. Lamarque expressed a vision of separation between a small subset of CMIP7 experiments including the DECK, historical, scenarios, detection/attribution, and few other key experiments whose forcing and other specification would be timed to support the IPCC WG1 Assessment (i.e., released in 2024 to support a presumed IPCC AR7 WG1 report release in 2028) with all other “MIPs” kept separate from these central CMIP7 experiments. When some attendants expressed skepticism that the next round could be contained, Lamarque stressed that task teams are being formed for planning and implored USCMS members to take part in these task teams. One suggestion to clarify the scientific motivation for modeling centers to engage in CMIP was to focus on something like three main challenges and goals that would galvanize the community for inspired participation.

Update: Lamarque participated in the above discussion in his role as the chair of the CMIP Panel. Since the Summit Meeting, Lamarque has resigned from his NCAR position as the director of the Climate and Global Dynamics Laboratory as well as from the CMIP Panel. Also considering V. Balaji's departure from GFDL, neither the CMIP Panel nor the Working Group on Coupled Modeling (WGCM) has any members from the US modeling centers who are actively involved with their coupled models². One new connection is Vaishali Naik at GFDL having joined the WCRP CMIP Task Team on Climate Forcing.

Perspectives Manuscript on Next Generation Predictions and Projections: Annarita Mariotti from the NOAA Climate Program Office (CPO) has been leading a perspectives manuscript on “Transforming US climate predictions and projections to meet new challenges” to be submitted to the Proceedings of the National Academy of Sciences (PNAS). The authors of the manuscript

consist of the USCMS participants and a few program managers, noting that the paper presents views of the authors and not necessarily those of their institutions or agencies. Mariotti provided the rationale and an overview of the manuscript. In the presence of climate change, better understanding, predictions, and projections of the Earth system are increasingly crucial and urgently needed to prepare for extremes and cascading hazards, understand unexpected feedbacks and potential tipping points, inform long-term adaptation strategies, and help guide mitigation approaches. Such information is needed increasingly at regional and local scales for use of decision makers and stakeholders. The US modeling, predictions, and projections enterprise and its partners are uniquely positioned to explore the development of credible and robust next-generation predictions and projections. This enterprise includes federally-funded climate modeling groups, academic research institutions, private sector players, and international partners. The manuscript outlines perspectives for a national approach that builds on the strengths of the US modeling community and agency plans to accelerate progress on climate predictions and projections to meet the new challenges posed by climate change. A focus is on collectively capitalizing on transformative opportunities, augmenting and complementing current modeling center capabilities and plans to support agency missions.

² Karl Taylor and Paul Durack – both from DOE LLNL PCMDI – continue to serve on the CMIP Panel, but they are not directly involved with coupled model development efforts.

Climate Model Data Storage and Accessibility Challenges – NSF EarthCube Workshop: What about model data? Gokhan Danabasoglu presented a summary of the hybrid Workshop that was held in Grand Forks, ND during 25-27 July 2022. The related project has been funded by the NSF. The topic of the Workshop is of interest to the center participants as they deal with model data. Evolving community open access expectations have led to data management requirements from funding agencies and publishers. However, data management requirements for simulation output have not been clear. Simply put, all the data from all the projects cannot be preserved – too expensive and not all the data are relevant or useful. Thus, the project and the Workshop aimed to bring together a diverse group of modeling experts, model data users, publishers and editors, data and technology experts, and early career scientists to develop simulation output preservation guidance; develop a rubric to guide researchers in determining what model output to preserve and share to communicate knowledge; refine rubric with extensive set of use cases; and disseminate a best practices document to broader community. Such a rubric has been created and presented to the community. An important aspect is that the primary goal in Earth science is replicability of research results, not necessarily exact computational reproducibility. Given this distinction, the goal should be to provide enough information about a workflow and selected derived outputs to communicate the important environmental characteristics to allow a future researcher to reproduce the fundamental result and build off of the original study, but not necessarily bit-reproduce answers. For highly nonlinear simulation studies, computational reproducibility should not be expected, nor is it needed. Findings that only work when bit reproducibility is needed are problematic to begin with for others to build on. It was also stated that improved technological capabilities, including cloud storage, are critical to dealing with model data, but they do not solve all data preservation needs and that without investment in data

curation personnel, the potential benefits of improved technological capabilities will not be realized. Several cultural barriers were also identified as impeding progress. For example, researchers need to be rewarded for support of collaborations through public provision of data, not for the data and software hoarding that may give them exclusive opportunities to provide their data and software to a select few of their choice. Rather, encouragement for open software and open data provision should exceed such motivations for retaining exclusive access. The workshop provided recommendations on sustainable curation; determining lifetime for simulation data; incentivizing data and software preservation and sharing; and equitable access to data and software curation and analysis resources.

CERESMIP: V. Ramaswamy, Susanne Bauer, and Steven Pawson led a discussion on a possible new MIP among the centers focused on understanding the trends in the satellite observations by Clouds and the Earth's Radiant Energy System Energy Balance and Filled (CERES EBAF) since 2003. A recent study by Raghuraman et al. (2021)³ reported a significant positive globally averaged energy imbalance trend at the top of the atmosphere for the recent period. They further found that this trend cannot be due to internal variability, and attributed the trend to a large decrease in reflected solar radiation and a small increase in emitted infrared radiation. However, many aspects of this trend remain unexplored. The proposed MIP – referred to as CERESMIP – would be mainly AMIP-style runs, that is, atmosphere-only, using updated forcings from 2000 through 2021, which would allow us to explore to what extent the shortwave trends in CERES data can be explained as either cloud feedbacks to greenhouse gas changes, internal variability,

³ Raghuraman, S. P., D. Paynter, and V. Ramaswamy, 2021: Anthropogenic forcing and response yield observed positive trend in Earth's energy imbalance. *Nature Comm.*, **12**, 4577, doi: 10.1038/s41467-021-24544-4.

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aerosol forcings, indirect effects, or a combination of these. AMIP runs are inexpensive, and if there is a coordinated effort this could be done relatively quickly. The modeling centers expressed enthusiastic interest in this project. The discussions indicated value of considering fully-coupled simulations as well. As an action item, Ramaswamy, Bauer, Pawson, and Gavin Schmidt were tasked with coming up with a detailed draft CERESMIP protocol that can be circulated among the modeling centers as a first step.

Ensemble Strategies and (Coupled) Data Assimilation in Earth System Modeling and Predictions: John Dunne and Vijay Tallapragada updated the Summit participants on the ever growing scope and applications of climate model ensembles; the increasing scope of Earth system processes, including land surface, soil, ecosystems, and ocean biogeochemistry, being considered for different applications; and the suite of data assimilation technologies being applied. Various participants stressed the potential benefits and synergies in modeling centers taking advantage of the Joint Effort for Data assimilation Integration (JEDI) and their interest in both the upcoming release from NCEP to supersede the CFS 1982-2010 reanalysis and stimulating research to evaluate and improve the North American Multimodel Ensemble (NMME), particularly identifying where additional aspects of independence can be integrated to increase the robustness of the ensemble mean.

Climate Process Teams (CPTs): John Dunne and Gokhan Danabasoglu stressed that the CPTs continue to be an extremely valuable mechanism for efficiently and quickly translating the latest

science into improved model parameterizations, establishing a common language and reconciling disagreements across observations, theory, and modeling communities. Partnerships in these activities continue to be vigorous with NCAR and GFDL collaborating in 5 active CPTs on atmosphere (2), land (2), and ocean (1) related processes with DOE and NASA each also participating in 3 of these efforts. Agency representatives – Jin Huang (NOAA), Xujing Davis (DOE), David Considine (NASA), and Eric DeWeaver (NSF) – indicated that the CPTs have been very successful and that they view them very favorably. An action item moving forward is to solicit both the modeling centers and the IGIM on their priorities for future CPTs.

Global Precipitation Experiment (GPEX): Jin Huang from the NOAA CPO provided an introduction to GPEX as well as an update on the status of a related white paper. The IPCC Six Assessment Report (AR6) indicated that the state-of-the-art climate models have high uncertainties in precipitation projections and little confidence in the attribution of human-caused impacts on precipitation and droughts. Specifically, related model systematic errors include: underestimation of heavy rain and overestimation of light rain events; the diurnal cycle of precipitation, with maxima too early in the day; initiation of convective precipitation, often due to errors in representation of boundary layer and convective parameterizations; slow or non physical propagation of convection; incorrect phase speed of mid-latitude troughs; and sub seasonal tropical variability. Similar systematic errors exist in both weather and climate models. So, improving key processes associated with precipitation can provide benefits for information on timescales of weather through climate change. To address these issues, NOAA and DOE jointly organized a Workshop on Precipitation Processes and Predictability with a report

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published in May 2021 summarizing key findings⁴. The USGCRP agencies proposed the initial concept of GPEX which is now adopted by the WCRP with participation of several US agencies, including NOAA, DOE, NASA, and NSF. GPEX is envisioned to be a multi-year (5-10 years) project with national and international participation and collaboration, aiming to systematically and comprehensively reduce model biases in global coupled models and improve precipitation prediction using an integrated observations and modeling strategy, targeting critical processes and phenomena. WCRP has appointed a GPEX Tiger Team to prepare a GPEX White Paper – a draft of which has been developed and its initial review by various WCRP entities has just been completed. WCRP will appoint a GPEX Planning Group to prepare the GPEX Science and Implementation Plan after the white paper is accepted. The proposed new activities include: supporting the establishment and/or expansion of global and regional precipitation databases; supporting the establishment of multi-model databases along with common evaluation metrics; supporting research on precipitation predictability, prediction techniques and applications on multi-year to multi-decadal timescales; and supporting existing national and regional activities and capacity building.

Miscellaneous Updates: Gary Geernaert, the acting director of DOE's Office of Biological and Environmental Research, provided updates on several topics of interest to the modeling centers, conveying information on various high-level ongoing and planned activities at government

agencies and climate-related committees. Topics covered by Geernaert included machine learning, wildfires, (solar) geoengineering, mountain hydrology, clean energy, tipping points, and coastal science. The latter topic has several areas of interest, i.e., offshore hypoxia, sea level rise, social impacts, decision making, and terrestrial effects. In addition, urban-related research will garner renewed attention.

Plans for the 9th USCMS

For the 2023 meeting (the 9th USCMS), the group agreed that Ruby Leung (PNNL) and John Dunne (GFDL) would co-chair the meeting. The meeting is anticipated to be a hybrid event with its location TBD. An expressed desire is to have the meeting earlier in the year, perhaps in early Spring, returning to the timeline of the earlier USCMS meetings. The topic of next year's workshop will be on *oceans' role on air – sea coupled climate interactions*. More detailed ideas will be discussed among the co-chairs in coordination with the modeling centers and the IGIM over the next year.

Closing Thoughts

The Summits and the associated Topical Workshops continue to provide a unique opportunity to enhance our collective understanding of changes in the emergent properties of the models; share plans, implementations, and challenges among the groups; collectively identify opportunities for further strengthening coordination among the groups; and productively work on such common projects and opportunities of interest. A concern raised by the modeling center participants was the rather sparse participation of the program managers both at the Topical Workshop and the

⁴ The Report is available at https://cpo.noaa.gov/Portals/0/Docs/ESSM/Events/2020/NOAA_DOE_PrecipWorkshopReport_July2021.pdf?ver=2021-07-14-160100-057

Summit Meeting. This lack of engagement by the IGIM and the program managers was keenly felt as a missed opportunity for feedback and engagement. Ways to solicit increased engagement with these participants should be encouraged in future USCMS.

**USCMS Topical Workshop on
Water Cycle and Water Security**

2-3 August 2022
(All times are EDT)

2 August 2022 (Tuesday)

Chair: Gokhan Danabasoglu

09:00 Gary Geernaert: Welcome and Background

09:10 Ruby Leung: Workshop objectives and outcomes

Session 1: Modeling water cycle and water security: model development and evaluation

09:15 Elena Shevliakova: GFDL updates on modeling precipitation and land-atmosphere interactions (remote)

09:30 Dave Lawrence: CLM updates on modeling water cycle and water security (remote)

09:45 Ben Bond-Lamberty: E3SM updates on modeling terrestrial water cycle processes (in person)

10:00 Nate Chaney: Representing subgrid scale water processes (remote)

10:15 *Break*

Chair: Dave Bader

10:35 Darren Engwirda: Modeling land-river-ocean processes in coastal zone (remote)

10:50 Bryce Harrop: Evaluation of E3SM using water cycle metrics (remote) 11:05 Ruby

Leung: Charge for breakout groups and anticipated outcomes 11:10 *Breakout discussion*

Group A: Lamarque, Harrop

Group B: Ramaswamy, Chaney

Group C: Tallapragada, Engwirda

12:10 *Lunch*

Session 2: Water cycle and water security: insights from observations and modeling *Chair: John Dunne*

13:00 Ben Cook: Global projections of drought in CMIP6 ensembles (remote)

13:15 Isla Simpson: Discrepancy between models and observations in historical hydroclimate

trends (remote)

13:30 Tricia Lawston: Progress and challenges in monitoring and modeling of irrigation (remote)

13:45 Yujin Zeng: Anthropogenic enhancement of precipitation in the Sahel-Sudan savanna by remote agricultural irrigation (remote)

14:00 Yadu Pokhrel: Global water cycle modeling and food-energy-water nexus (remote)

14:15 Tian Zhou: Impact of climate change and water management on floods (remote)

14:30 *Break*

Chair: Susanne Bauer

14:50 Amir AghaKouchak: Compound extreme events (remote)

15:05 Andy Wood: Model representations of runoff sensitivity (remote)

15:20 Ruby Leung: Reduced relative humidity over land with warming and implications for convection (in person)

15:35 Allegra LeGrande: Understanding atmospheric river changes using water tracers (remote)

15:50 Kai-Chih Tseng: Are multiseasonal forecasts of atmospheric rivers possible? (remote)

16:05 Bor-Ting Jong: Increasing occurrence of extreme precipitation over the Northeast United States: Using an ensemble of high-resolution climate model simulations (in person)

16:20 *Breakout discussion*

Group A: Pawson, LeGrande

Group B: Bauer, Jong

Group C: Gokhan, Pokhrel

17:20 *Adjourn for the day*

3 August 2022 (Wednesday)

Session 3: Emerging approaches for modeling water cycle and water security: Ultra-high resolution modeling and AI/ML

Chair: Steven Pawson

08:30 Gokhan Danabasoglu: NCAR activities (in person)

08:45 Vijay Tallapragada: NCEP activities (in person)

09:00 Lucas Harris: A global view of moist convective processes using GFDL X-SHiELD (remote)

09:15 Peter Caldwell: Global storm-resolving modeling in E3SM (remote)

09:30 Shahryar Ahmad: Understanding non-stationarities in the water cycle with machine learning (in person)

09:45 Clara Orbe: GISS activities (remote)

10:00 *Break*

Chair: Vijay Tallapragada

10:20 Tapio Schneider: Machine learning within parameterizations as an inverse problem: Toward stable and generalizable models (in person)

10:35 Andy Prein: Kilometer-scale modeling of the hydrologic cycle: Lessons learned and challenges ahead (remote)

10:50 Naresh Devineni: The role of big data analytics in securing the future of water, energy and food (remote)

11:05 *Breakout discussion*

Group A: Bader, Orbe

Group B: Dunne, Prein

Group C: Gross, Harris

12:05 Breakout report back (Session 1: 5 min per group)

12:20 Breakout report back (Session 2: 5 min per group)

12:35 Breakout report back (Session 3: 5 min per group)

12:50 *Adjourn for the workshop*

Presentations for the Workshop, including the breakout summaries, can be found at:

<https://drive.google.com/drive/folders/13mkafDS4gccUEBU3uq4zM7TrvP6KbzsQ>

Appendix B: The 8th USCMS Agenda

All times are EDT

03 August 2022 (Wednesday)

- 13:30 Welcome and Introductions (Gokhan Danabasoglu, Gary Geernaert)
- 13:45 Status of the World Avoided Experiment resulting from USCMS 2019 (Jean-François Lamarque)
- 13:55 Status of the Climate Sensitivity project resulting from USCMS 2020 (Johannes Muehlmenstaedt)
- 14:05 Status of the Predictability project resulting from USCMS 2021 (Gokhan Danabasoglu)
- 14:15 Summary of the Water Workshop and next steps (Ruby Leung)

Model group updates

What is new since last year in science, priorities, and challenges, focusing on USGCRP-relevant current activities

- 14:45 E3SM (Ruby Leung)
- 15:05 GFDL (V. Ramaswamy)
- 15:25 *Break*
- 15:45 GISS (Susanne Bauer)
- 16:05 GMAO (Nathan Arnold)
- 16:25 NCAR (Gokhan Danabasoglu)
- 16:45 NCEP (Vijay Tallapragada)

General Discussion Topics

- 17:05 Future outlooks: CMIP; WCRP; IPCC (John Dunne, Jean-Francois Lamarque)

17:45 Adjourn for the day

04 August 2022 (Thursday)

General Discussion Topics (continued)

08:30 Perspectives manuscript: Next generation predictions and projections (Annarita Mariotti)

08:45 Climate Model Data Storage and Accessibility Challenges – NSF EarthCube Workshop: What about model data (Gokhan Danabasoglu)

09:00 Other discussion items (All)

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CERESMIP: A mini-MIP to understand the CERES data trends since 2003
(Susanne Bauer, V. Ramaswamy, Steven Pawson)

Ensemble strategies and (coupled) data assimilation in Earth system modeling and predictions: Physics, chemistry, biogeochemistry, ecosystems (John Dunne, Vijay Tallapragada);

Climate Process Teams: Updates and inputs for the future (anticipated) calls (John Dunne, Gokhan Danabasoglu); other center perspectives; also from funding agencies: Jin Huang, Xujing Davis, Eric DeWeaver, David Considine

Global Precipitation Experiment (GPEX) (Jin Huang);

Updates on several topics of interest to modeling centers: Urban, coastal, ML / AI, geoengineering, wildfire, mountain hydrology (Gary Geernaert)

10:30 *Break*

10:50 Continue discussion of the above items, including an assessment of where we are

11:30 Review action items; Leadership for the next year

Next Year's Workshop: Theme and co-chairs

12:15 Adjourn

Presentations for the Summit can be found at:

<https://drive.google.com/drive/folders/1P12slMPT6IxJTkoQKTEst6xSDEEZuCzm>

Appendix C: Modeling Center Representatives in Attendance

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⁵In place of Gavin Schmidt (NASA/GISS)

⁶In place of Bill Putman (NASA/GMAO)